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Preheating in the Universe Suppressing High Energy Gamma-rays from Structure Formation

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Structure formation in the universe can produce high energy gamma-rays from shock-accelerated electrons, and this process may be the origin of the extragalactic gamma-ray background (EGRB) as well as a part of the unidentified sources detected by EGRET in the GeV band, if about 5% of the kinetic energy of the shock is going into electron acceleration. However, we point out that the production of gamma-rays may be severely suppressed if the collapsing matter has been preheated by external entropy sources at the time of gravitational collapse, as can be inferred from the luminosity-temperature (LT) relation of galaxy clusters and groups. We also make a rough estimate of this effect by a simple model, showing that the EGRB flux may be suppressed by a factor of about 30. Hence structure formation is difficult to be the dominant origin of EGRB if preheating is actually responsible for the observed anomary in the LT relation. The detectable number of gamma-ray clusters is also reduced, but about 5–10 forming clusters should still be detectable by EGRET all sky, and this number is similar to that of the steady and high-latitude unidentified sources in the EGRET catalog. The future GLAST mission should detect 10^2–10^3 gamma-ray clusters of galaxies even if the intergalactic medium has been preheated.

I. INTRODUCTION

It is widely believed that the observed structures in the universe have been produced via gravitational instability. Currently the most successful theory of structure formation is the cold dark matter (CDM) scenario, in which the structures grow hierarchically from small objects into larger ones. When an object collapses gravitationally and virializes, the baryonic matter in the object is heated by shock waves up to the virial temperature, and particles are expected to be accelerated to high energy by shock acceleration. High energy gamma-rays are then expected to be produced during structure formation, via inverse-Compton scattering of cosmic microwave background photons by high energy electrons. Recently, Loeb & Waxman [1] speculated that this process can be the origin of the extragalactic gamma-ray background (EGRB) observed at $\sim$ 1–100 GeV [2], if about 5% of the post-shock thermal energy is going into electron acceleration. Totani & Kitayama (Paper I [3]) has shown that, if this is the case, a few tens of forming clusters should have already been detected by the EGRET experiment which has performed an all sky survey in the GeV band [4], and a part of the unidentified EGRET sources can be accounted for (see also Waxman & Loeb [5]).

All these analyses are based solely on hierarchical structure formation in the CDM universe, but recent x-ray observations of clusters and groups of galaxies have shown that the x-ray properties of these objects cannot be explained by the above simple picture of hierarchical structure formation alone. It is well known that the luminosity-temperature (LT) relation of clusters and groups is considerably different from what is expected from the self-similar model predicted by hierarchical structure formation (e.g., [6–8]). The most popular explanation is that the intergalactic medium has been preheated by external entropy sources such as supernovae or active galactic nuclei up to a temperature of about 1 keV (e.g., [9–11]).

If this is the case, gamma-ray production from structure formation should be significantly suppressed, because the external entropy impedes the gravitational collapse and weakens the shock, resulting in decreased shock heating and softer spectra of accelerated particles. It should be noted that the objects on which preheating has the most significant effect ($M \sim 10^{14} M_\odot$ and $T \sim 1$ keV) are those which are expected to produce most of the EGRB photons. In this letter we try to make a quantitative estimate of the preheating effect on the production of gamma-rays from structure formation.

Throughout this paper, we assume a CDM universe with the density parameter $\Omega_0 = 0.3$, the cosmological constant $\Omega_\Lambda = 0.7$, the Hubble constant $h =$

$H_0/(100\mathrm{km/s/Mpc}) = 0.7$, the baryon density parameter $\Omega_B = 0.015h^{-2}$, and the density fluctuation amplitude $\sigma_8 = 1$. These parameters are favored from various recent cosmological observations.

II. EFFECT OF PREHEATING ON STRUCTURE FORMATION

The formulation for calculating the EGRB flux and source counts of gamma-ray clusters when there is no preheating has been given in Paper I. Here we describe the modification to include the effect of preheating. There are two important effects of preheating on the production of high energy gamma-rays from structure formation. The first is that the external entropy leads to the virialization of collapsing gas at a larger radius with smaller infalling velocity and smaller kinetic energy of shock compared with the no-preheating case. The second is that the external entropy results in a smaller Mach number and a shock which is no longer ideally strong, and hence the energy spectrum of accelerated electrons should be significantly softer than that without preheating.

It is not easy to predict realistic density profiles for preheated, collapsing gas without recourse to detailed numerical simulations, even in the spherically symmetric, one-dimensional case (e.g., [12,11]). In the following discussion, we do not inquire about the actual distribution of the baryonic matter within the dark matter halo, and the relevant physical quantities are to be interpreted in a volume-averaged sense. It should be noted, however, that the production of gamma-rays is less sensitive to the gas density profile than, e.g., the x-ray luminosity of thermal bremsstrahlung because the target photons for inverse-Compton scattering into gamma-rays are the CMB photons whose density is universal. Thus we believe that the following simplified treatment is an adequate first approximation for the estimate of gamma-ray production, although it may be too simple to calculate accurately the x-ray luminosity and temperature of clusters of galaxies.

We calculate the virial radius (r_h) and the velocity of collapsing, preheated baryonic gas (V_h) at virialization by a simple model naturally extended from the standard spherical collapse model (e.g., [13]). Let us start from the energy conservation equation of baryonic gas with mass $M_B = (\Omega_B/\Omega_0)M$ originally embedded in a dark halo with mass M:

$$\frac{1}{2}M_B V^2 - \frac{GM_B M}{r} + \frac{M_B a^2}{\Gamma(\Gamma-1)} = -\frac{GM_B M}{2r_{\rm vir}} + \frac{M_B a_0^2}{\Gamma(\Gamma-1)} \ , \qquad (1)$$

where r is the characteristic radius of the collapsing gas, and $V = dr/dt$ is the infalling velocity. We ignore the heating or cooling during the collapse and assume the collapse proceeds adiabatically, and then the effect of preheating is to add the internal energy $M_B a^2/[\Gamma(\Gamma-1)]$, where $a = (dP/d\rho_B)^{1/2}$ is the sound velocity. The pressure P is related to the density through the entropy parameter K as $P = K\rho_B^\Gamma$, and the baryon gas density is $\rho_B = M_B/(4\pi r^3/3)$. The right hand side of this equation is the total energy of this system, estimated at maximum expansion ($r = 2r_{\rm vir}$), where $r_{\rm vir}$ is the virial radius when there is no preheating. The sound velocity $a = (dP/d\rho_B)^{1/2}$ is related to that at maximum expansion a_0 as $a = (r/2r_{\rm vir})^{-1.5(\Gamma-1)}a_0$.

The virialization of the system is expected to occur at a radius of r_h which is larger than $r_{\rm vir}$ because of preheating. We estimate this by simply extending the virial theorem for this system, resulting in the following equation at virialization:

$$M_B V^2 = \frac{GM_B M}{r} - \frac{3M_B a^2}{\Gamma} \ . \qquad (2)$$

Therefore, V_h and r_h are determined by solving equations 1 and 2. For the case of $\Gamma = 5/3$, the result is

$$r_h = GM\left[\frac{GM}{r_{\rm vir}} - \frac{9}{5}a_0^2\right]^{-1} \ , \qquad (3)$$

and

$$V_h = \left[\frac{GM}{r_h} - \frac{9}{5}a_0^2\left(\frac{2r_{\rm vir}}{r_h}\right)^2\right]^{\frac{1}{2}} \ . \qquad (4)$$

The above model is valid only so long as $r_h < 2r_{\rm vir}$; haloes with $r_h > 2r_{\rm vir}$ cannot collapse from the point of maximum expansion (turn around) and we assume that such haloes have radii $r_h = 2r_{\rm vir}$ and neither shocks nor gamma-rays are generated. The original virial radius $r_{\rm vir}$ can be calculated by the standard spherical collapse model for a dark halo of mass M collapsing at z, and then we can calculate the shock energy as the kinetic energy given to infalling baryonic gas, $(3/4)M_B V_h^2$, which is reduced compared with the no-preheating case.

Next we calculate the Mach number of the shock and spectral index of shock-accelerated particles. In the rest frame of the infall (i.e., undisturbed) gas, the propagation of the shock can be regarded as a problem of supersonic piston moving with the velocity of infall gas, V_h, measured in the cluster rest frame. The shock velocity V_s (i.e., the upstream gas velocity towards the shock in the rest frame of the shock front) is given as (e.g., [14]):

$$V_s = \frac{\Gamma+1}{4}V_h + \left[a^2 + \frac{(\Gamma+1)^2 V_h^2}{16}\right]^{\frac{1}{2}} \ , \qquad (5)$$

and the upstream Mach number is given by $\mathcal{M} = V_s/a$. The particle index is given by $\alpha \equiv -d(\log N_e)/d(\log \gamma_e) = (r+2)/(r-1)$, where $r = (\Gamma+1)/[(\Gamma-1)+2/\mathcal{M}^2]$ is the compression ratio and γ_e is the electron Lorenz factor.

We must determine an appropriate value of the entropy parameter, K, so that the above model is consistent with the observed LT relation of clusters and groups. We parametrize the entropy parameter as $K = K_{34,0}(1+z)^{-1}10^{34}\text{erg cm}^2\text{g}^{-5/3}$, assuming the redshift dependence of $K \propto (1+z)^{-1}$ which is consistent with the observed LT relation [11]. Following Tozzi & Norman [11], we take the parameter $K_{34,0} \sim 0.8$ as a fiducial value to be consistent with the LT relation.

Figure 1 shows the typical parameters of preheated haloes as obtained above. It is clear that the objects with $M \sim 10^{14} M_\odot$ is seriously affected by preheating, with the particle acceleration index much softer than the strong-shock limit of $\alpha = 2$. Therefore cosmological objects less massive than $\sim 10^{14} M_\odot$ hardly contribute to the high energy gamma-ray background in the GeV band.

As mentioned above, our model may be too simple to calculate the x-ray luminosity and temperature of preheated haloes, since we have ignored the density profile within the halo to which the x-ray luminosity is very sensitive. In spite of this difficulty, however, our model reproduces the observed LT relation fairly well, as shown below. A simple scaling relation for the x-ray luminosity of thermal bremsstrahlung emission from cluster gas is $L \propto \rho_B T^{1/2}$ where T is the gas temperature. It is expected that most of the kinetic energy of collapsing matter calculated above is eventually converted into thermal energy. We estimate the temperature so that the final thermal energy is the total of this energy from gravitational collapse and the external energy of the preheating. Then the temperature of the preheated gas is given by $T_h = (V_h/V_c)^2 T_{\rm vir} + \mu m_p K \rho_B^{\Gamma-1}/k_B$, where V_c and $T_{\rm vir}$ are respectively the circular velocity and virial temperature of a halo without preheating predicted by the spherical collapse model. Here μ is the mean molecular weight and k_B is the Boltzman constant. The X-ray luminosity is then given by $L = (r_{\rm vir}/r_h)^3 (T_h/T_{\rm vir})^{1/2} L_{\rm SS}$, where $L_{\rm SS}$ is the x-ray luminosity of the self-similar model for non-preheated clusters of galaxies which is a function of cluster mass and formation redshift. We used the formula of Kitayama & Suto [15] for $L_{\rm SS}$.

Then we can calculate the luminosity and temperature of a preheated halo with mass M and collapsing at redshift z_F. Figure 2 shows the LT relation predicted for cosmological objects observed at $z_{\rm obs} = 0$, compared with observations. Objects should have various z_F even for the same mass, and here we utilize the distribution of z_F as a function of mass and $z_{\rm obs}$ derived by Lacey & Cole [16]. The thick solid line shows the LT relation when the median of the Lacey-Cole z_F distribution is applied, using the standard value of the entropy parameter: $K_{34,0} = 0.8$. The behavior of the model LT curve changes abruptly at $(L, T) = (10^{42.3}\text{erg s}^{-1}, 0.6 \text{ keV})$, and this corresponds to the point at which r_h becomes equal to the maximum expansion radius, $2r_{\rm vir}$, and hence haloes cannot gravitationally collapse. The dashed and dotted lines show the dispersion of the LT relation corresponding to that of z_F, encompassing 68% (1 σ) and 95% (2 σ) of the probability distribution of z_F, respectively. The thin solid lines are for median z_F, but with different values of $K_{34,0} = 0.4$ and 1.6. Figure 2 shows that our simple model is in reasonable agreement with the data when the same entropy parameter as Tozzi & Norman [11] is used.

Now we can calculate the EGRB flux and source counts of gamma-ray clusters by the formulation given in Paper I, simply replacing the shock energy and particle acceleration index by those obtained above. In the following we will apply the above model to calculate the EGRB flux and spectrum, and the expected counts of gamma-ray clusters.

III. EXTRAGALACTIC GAMMA-RAY BACKGROUND

The efficiency of energy injection from the kinetic energy of infalling gas into nonthermal electrons by the shock acceleration acceleration is parametrized by ξ_e, and we assume 5% injection, i.e., $\xi_e = 0.05$ following Loeb & Waxman [1] and Paper I. It is widely accepted that low-energy cosmic rays are accelerated in supernova remnants, and its energy injection efficiency is about 1–10% for ions. On the other hand, injection into electrons is still highly uncertain, both observationally and theoretically. As is well known, the energy flux of cosmic-ray electrons observed above the Earth's atmosphere is about 100 times lower than that of cosmic-ray protons, and it may suggest that energy injection is considerably lower for electrons than for ions. However, the local cosmic-ray flux ratio does not necessarily reflect that at the production site, because of different energy loss and propagation processes. Hence, we take $\xi_e = 0.05$ as a maximally possible value, although it could be rather optimistic.

Figure 3 shows our calculation of the EGRB flux and spectrum based on the model described above. We have used a value of the magnetic field parameter, $\xi_B = 10^{-3}$, which is the ratio of magnetic energy to the total gravitational energy given to baryonic matter. Magnetic fields of $\xi_B \sim 10^{-3}$ are sometimes observed in intracluster mat-

ter, and the EGRB spectrum extends up to ~ 100 GeV if $\xi_B \gtrsim 10^{-5}$ (Paper I). Note that this parameter determines only the maximum photon energy of the EGRB spectrum, and the EGRB flux is rather insensitive to this uncertain parameter. It can be seen that the EGRB flux is severely decreased by a factor of about 30 for preheating of $K_{34,0} \sim 0.8$, which fits best to the observed LT relation. Even if we use a relatively small value of $K_{34,0} = 0.4$, the EGRB flux is about one order of magnitude smaller than that observed. Therefore, if the intergalactic medium is actually preheated, the structure formation is very unlikely to be the origin of EGRB. It should be noted that we have already assumed a relatively large efficiency of shock energy injection into electron acceleration, $\xi_e = 0.05$, and hence we cannot take the option of increasing this parameter to save this hypothesis.

IV. FORMING GAMMA-RAY CLUSTERS OF GALAXIES

The top panel of Fig. 4 shows the calculation of the source counts for gamma-rays from structure formation. Compared with the case of no preheating, the source counts are decreased by a factor of 10 above the EGRET sensitivity limit. See the bottom panel of the figure for the mean values of physical quantities of gamma-ray emitting objects (mass, redshift, and angular radius) brighter than a given flux. The mean spectral index for gamma-ray clusters detectable above 100 MeV is rather insensitive to the flux, increasing as $\alpha = 2.20$ to 2.26 from the sensitivity of the EGRET to that of GLAST, because only objects with sufficiently hard spectrum can be observed at GeV energies.

For the canonical value of the entropy parameter, $K_{34,0} = 0.8$, the number of gamma-ray clusters detectable by EGRET is about 5 in all sky. If we take a relatively small value of $K_{34,0} = 0.4$ to account for the model uncertainty, the number is increased to 14. These numbers are smaller than those reported by Paper I because of the preheating effect, but it is interesting to note that the number of steady (i.e., unlikely to be AGNs) unidentified sources of the EGRET catalog presented in Gehrels et al. [18] is 7 for $|b| > 45^\circ$ ($\sim 24 \pm 9$ in all sky), which is not very different from our result. A significant part of these high-latitude, steady unidentified EGRET sources could be explained by dynamically forming gamma-ray clusters.

V. CONCLUSION

We have shown that the preheating of intergalactic medium, which may have occurred as indicated from the observed x-ray properties of clusters and groups of galaxies, significantly suppresses the production of high-energy gamma-rays from structure formation. If preheating is actually responsible for the steepening in the LT relation, structure formation cannot be the dominant origin of EGRB. The number of discrete sources detectable by the EGRET is also decreased by preheating, but 5–10 gamma-ray clusters could still be observable all sky, which may constitute a part of the unidentified sources. Even if the preheating effect is profound, the future GLAST mission may detect about 100–1000 gamma-ray clusters, and it may be used to probe the preheating processes in the intergalactic medium as well as the dynamical processes of structure formation.

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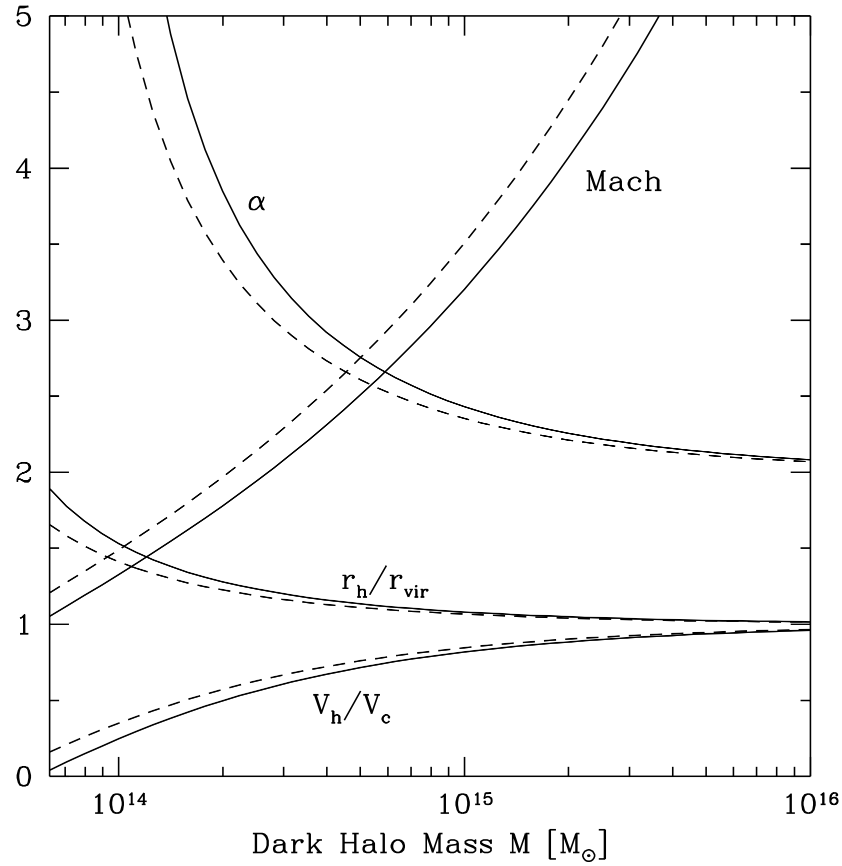

FIG. 1. The virial radius (r_h) and velocity (V_h), Mach number, and particle acceleration index (α) of gravitationally bound objects under the effect of preheating, as a function of dark halo mass. The radius and velocity are given as the ratios to the original virial radius ($r_{\rm vir}$) and velocity (V_c) in the case of no-preheating. The solid line is for the objects forming at $z_F = 0$, while the dashed line for $z_F = 1$. The entropy parameter is assumed to be $K = K_{34,0}(1+z)^{-1}10^{34}$erg cm^{2}g$^{-5/3}$ with $K_{34,0} = 0.8$.

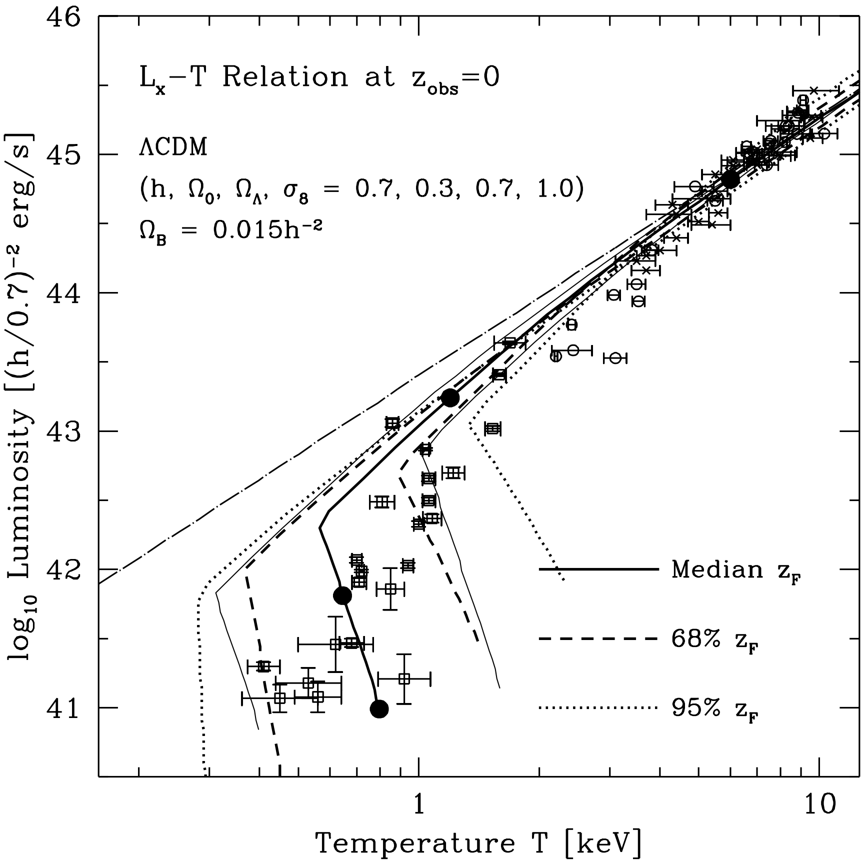

FIG. 2. The x-ray luminosity-temperature (LT) relation of galaxy clusters and groups. The thick-solid line is the model prediction for objects observed at $z_{\rm obs} = 0$, using the median of the Lacey & Cole [16] distribution function for the formation redshift (z_F). The entropy parameter is assumed to be $K = K_{34,0}(1+z)^{-1}10^{34}{\rm erg\ cm^2g^{-5/3}}$ with $K_{34,0} = 0.8$. The solid circles are indicating the grids corresponding to the cluster masses of $10^{12}, 10^{13}, 10^{14}$, and $10^{15}M_\odot$. The dashed and dotted lines show the dispersion of the LT relation due to that of z_F, in which z_F is included by a probability of 68% (1 σ) and 95% (2 σ), respectively. The two thin-solid lines are the same as the thick-solid line, but for different values of the entropy parameter, $K_{34,0} = 0.4$ and 1.6. The dot-dashed line is the prediction of the self-similar model of x-ray luminosity of clusters without preheating, assuming $z_F = z_{\rm obs} = 0$. The data points are from Markevitch (cross, [6]), Arnaud & Evrard (open circle, [7]), and Helsdon & Ponman (open square, [8]).

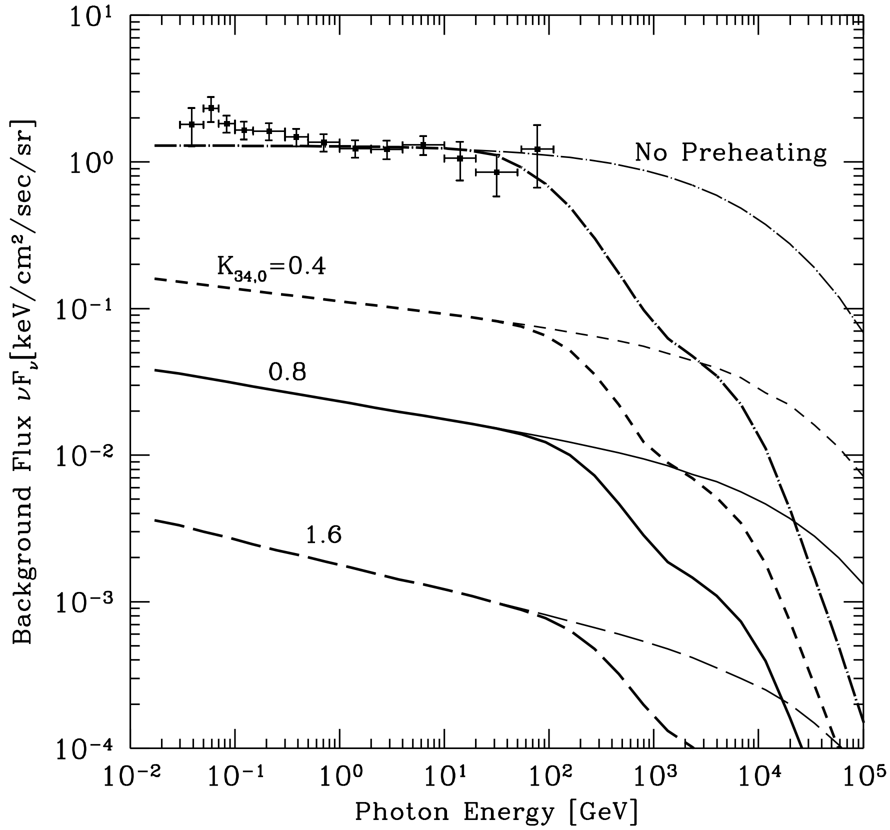

FIG. 3. The spectrum of the cosmic gamma-ray background (EGRB) in the GeV band expected from structure formation. The short-dashed, solid, and long-dashed lines are for the entropy parameters of $K_{34,0} = 0.4$, 0.8, and 1.6, where $K = K_{34,0}(1+z)^{-1}10^{34}\text{erg cm}^2\text{g}^{-5/3}$. ($K_{34,0} = 0.8$ best fits to the observed LT relation of galaxy clusters.) The dot-dashed line is the result of Paper I without the effect of preheating. All thick lines take into account the absorption of gamma-rays in the intergalactic field using the opacity presented in Totani (2000) [17] while the thin lines do not. (Reproduction of gamma-rays is not taken into account in either case, see Paper I). The observed data are from Sreekumar et al. (1998) [2].

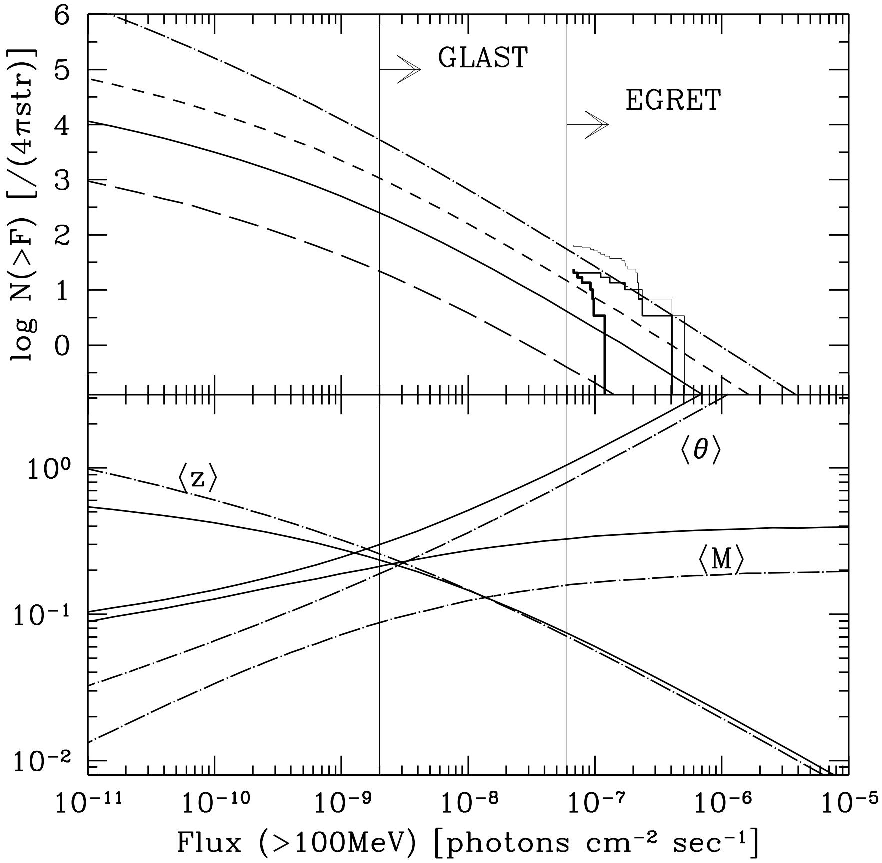

FIG. 4. The upper panel: the cumulative flux distribution of gamma-ray emitting clusters of galaxies. The four curves are for different values of the entropy parameter, $K = K_{34,0}(1+z)^{-1}10^{34}$ erg cm^2 g$^{-5/3}$, with $K_{34,0} = 0$ (no preheating, dot-dashed), 0.4 (short-dashed), 0.8 (solid, best fits to the LT relation), and 1.6 (long-dashed). The observed distribution of the unidentified EGRET sources with $|b| > 45^\circ$ is shown by the three solid lines, corresponding to all unidentified sources, 'em' sources (see Paper I), and steady unidentified sources defined by Gehrels et al. (2000) [18], with the order of the line thickness from thinner to thicker. The sensitivity limits of the EGRET and GLAST experiments are shown in the figure. The lower panel: the mean redshift, cluster mass (in units of $10^{16}M_\odot$), and angular radius (in degree) of gamma-ray clusters brighter than a given flux are shown. The line markings are the same as the upper panel.